Transactions of the Royal Society of S. Aust. (2002), **126**(2), 91-102.

STRATIGRAPHY OF THE LAKE MALATA PLAYA BASIN, SOUTH AUSTRALIA

by A. Dutkiewicz* & C. C. Von Der Borch†

Summary

Dutkiewicz, A. & von der Borch, C. C., (2002). Stratigraphy of the Lake Malata Playa Basin, South Australia. *Trans. R. Soc. S. Aust.* **126**(2), 91-102, 29 November, 2002.

The 19 m-thick Late Quaternary stratigraphic sequence within Lake Malata, Eyre Peninsula is dominated by autochthonous gypsum, present as relatively mud-free gypsarenites and gypsum-clay laminae overlying a skeletetal peloidal grainstone of the Bridgewater Formation near the base of the lacustrine succession. Calcite and dolomite mud are minor components of the column and several metres of these deposits appear to have been deflated into marginal lunettes. The skeletal peloidal grainstone has been severely modified by dissolution and formation of phreatic calcite, dolomite and gypsum cements under alternating pluvial and arid conditions. Discrete units are separated by disconformities and attest to rapid changes in climatic and hydrologic conditions over the lower Eyre Peninsula, commencing with emplacement of the Bridgewater Formation ca. 400 ka.

Key Words: Quaternary palaeoclimate, salt lakes, Lake Malata, Bridgewater Formation, carbonate mud, gypsum, dolomite, Eyre Peninsula.

Introduction

Lake Malata is an ephemeral salt lake situated 33 m above mean sea level in a mid-latitude region on lower Eyre Peninsula, South Australia (Fig. 1). It covers a total surface area of around 21 km^2, which excludes numerous small deflationary playa lakes to the east of the main basin. Lake Greenly, 10 km south-west of Lake Malata, forms another major playa lake in the region but appears not to have been connected to Lake Malata in the relatively recent past (Dutkiewicz 1996)[1] and indeed has a different stratigraphic sequence (Dutkiewicz & von der Borch 1995). Notably, Lake Malata is dominated by autochtonous evaporite deposits which are interbedded with carbonate mud, whereas Lake Greenly is dominated by carbonate muds interbedded with minor evaporites. Lake levels in Lake Malata fluctuate rapidly and seasonally as a consequence of surficial hydrological closure and rapid changes in the inflow-evaporation balance, which relies heavily on regional rainfall. During the wet winter season the lake retains < 0.5 m water, which evaporates in summer leaving behind a cm-thick halite crust. Although there is little direct evidence for the origin of the lake, geomorphologically its formation appears to have coincided with the emplacement of the Bridgewater Formation sub-parabolic dunes during late Quaternary sea-level high stands. These dunes, which consist of skeletal peloidal sands, may have effectively dammed the pre-Pleistocene drainage channel thus forming local depocentres. Also, as the Bridgewater Formation forms the main recharge aquifer in the region, groundwater seepage along the dune lobes would have invariably enhanced lake basin formation within interdunal corridors and in

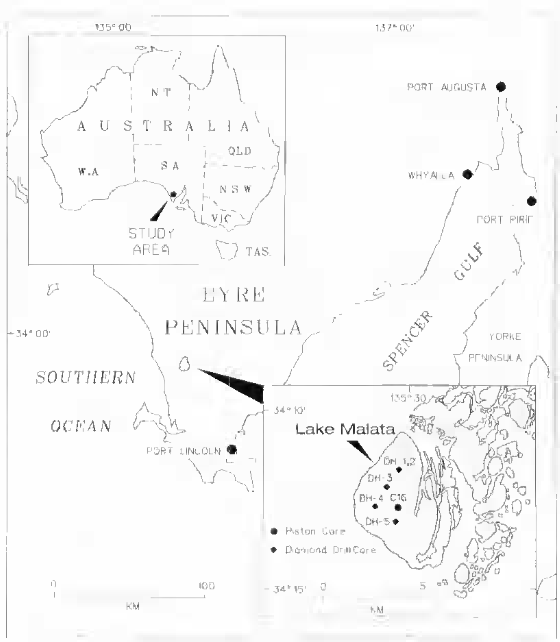


Fig. 1. Map of Eyre Peninsula showing Lake Malata and location of sediment cores.

* School of Geosciences, Building F05, The University of Sydney NSW 2006, Australia

† School of Chemistry, Physics and Earth Sciences, Flinders University, GPO Box 2100, SA 5001, Australia

[1] Dutkiewicz, A. (1996) "Quaternary Palaeoclimate from Lake Malata-Lake Greenly Playa Complex, South Australia" PhD thesis, The Flinders University of South Australia (Unpubl.).

areas of low relief. Prominent geomorphological features include clay pellet lunettes, gypsum lunettes and beach deposits along the eastern margins of most playa basins (Dutkiewicz *et al.* 2002) some of which reach 9 m in height. Apart from the sub-parabolic dunes, pisolitic red soils and calcrete of possible Tertiary age dominate the geomorphology to the south and west of the main basin (Dutkiewicz *et al.* 2002).

This paper focuses on the sedimentary succession within Lake Malata, which provides evidence of past fluctuations in lake level, groundwater chemistry, and Quaternary climates. The carbonate-evaporite cycles reflect hydrologic and geomorphologic settings of the basin, detrital influx, groundwater seepage and recharge, and wind shear, which often redistributes surface water and wet sediment across the entire lake surface and deflates dry sediment into marginal lunettes. Post-depositional diagenesis of primary and clastic carbonates and evaporites will be discussed briefly as these also have been influenced by climatic oscillations.

Methods

The stratigraphic sequence is based chiefly on five diamond drill cores taken from the main basin in 1987 by Gilfillan and Associates Pty. Ltd. to determine the viability of gypsum mining (Fig. 1). The cores sampled the lake sequence to basement and are available for viewing at the South Australian Department of Mines and Energy core library in Glenside, Adelaide. Despite their deteriorated state, compaction of up 60% and 80% recovery, careful sampling and detailed petrographic study of about 50 thin sections allowed a stratigraphic succession and palaeoenvironmental reconstruction to be established for Lake Malata. Unfortunately, sediments from the drill cores were unsuitable for radiocarbon and thermoluminescence dating due to contamination, exposure to sunlight, and paucity of suitable material available for dating. Consequently, a piston coring method was used to sample 1.8 m of fresh sediment from the center of Lake Malata (Fig. 1). AMS dating of the sequence, however, was unsatisfactory due to high concentrations of Na, Mg and K salts and low organic carbon contents (Dutkiewicz 1996)[1].

All cores were logged and the mineralogy of selected horizons analysed in some detail. The colour was determined using the Munsell colour chart. Unconsolidated material was wet sieved; the coarse fraction was examined under a binocular microscope, and the composition of the fine fraction determined using X-ray diffraction. Consolidated material was cut perpendicular to bedding, impregnated and used for thin sectioning. The thin sections were partly stained with Alizarin red-S, and studied with a polarising microscope. Textures and cements were further examined using Scanning Electron Microscopy at CEMMSA at Adelaide University.

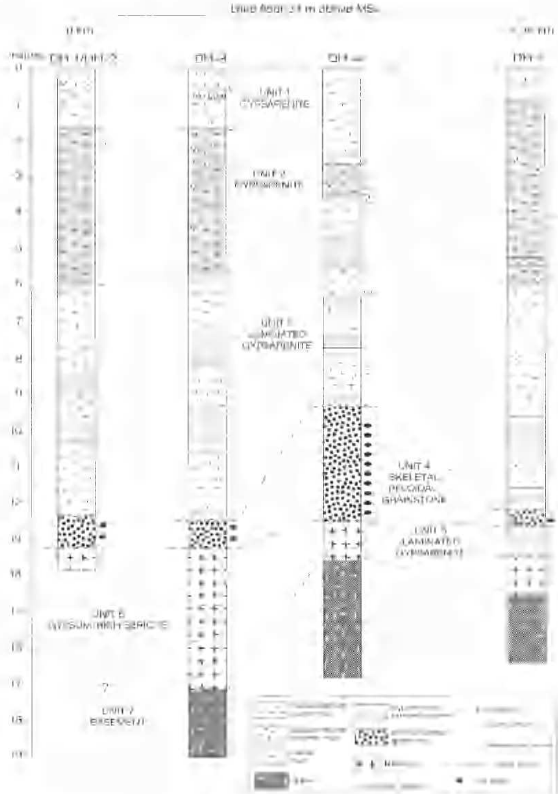


Fig. 2. Correlation of cores through the Lake Malata basin.

Gypsum samples in hand specimen are described using a grain-size classification scheme of Warren (1982) while primary and secondary gypsum petrofabric descriptions are based on criteria outlined by Bowler & Teller (1986) and Magee (1991). The skeletal peloidal sands and grainstones in Lake Malata have been correlated with calcareous aeolianites from the Bridgewater Formation using detrital, molluscan, foraminiferal, echinoderm, algal, bryozoal and peloidal compositional classes.

Stratigraphy

Gypsum constitutes at least 70% of the bulk sediment within the Lake Malata basin. Carbonate (calcite and dolomite) and detrital clays form a relatively minor component and occur as fine laminations or interbeds rather than discrete units. However, strandline deposits, which include several phases of carbonate pellet lunette and gypsum foredune deposition (Dutkiewicz *et al.* 2002), suggest that at least 5 m of carbonate mud and at least 10 m of gypsum sand have been removed from the lake basin during periods of deflation and lunette-building spanning ca. 115-6 ka (Dutkiewicz *et al.* 2002). Individual units comprising the most completely sampled succession from diamond drill core DH-5, which appears to have been taken from the palaeo-lake center, are discussed in detail. A cross-section through the Lake Malata basin using all available diamond drill cores is shown in Figure 2. Contacts between the individual units are sharp with disconformities between units 6, 5 and 4, and 6, 4 and 3.

Unit 7: Basement (Weathered Gneiss)

The basement consists of yellowish grey, very soft and highly weathered gneiss which contains abundant pebble and sand-sized grains of clear and grey quartz, sericite and iron oxides. The gneiss is exposed around the southern and eastern margin of Lake Malata where it forms a graben-type structure.

Unit 6: Gypsum-Rich Sericite

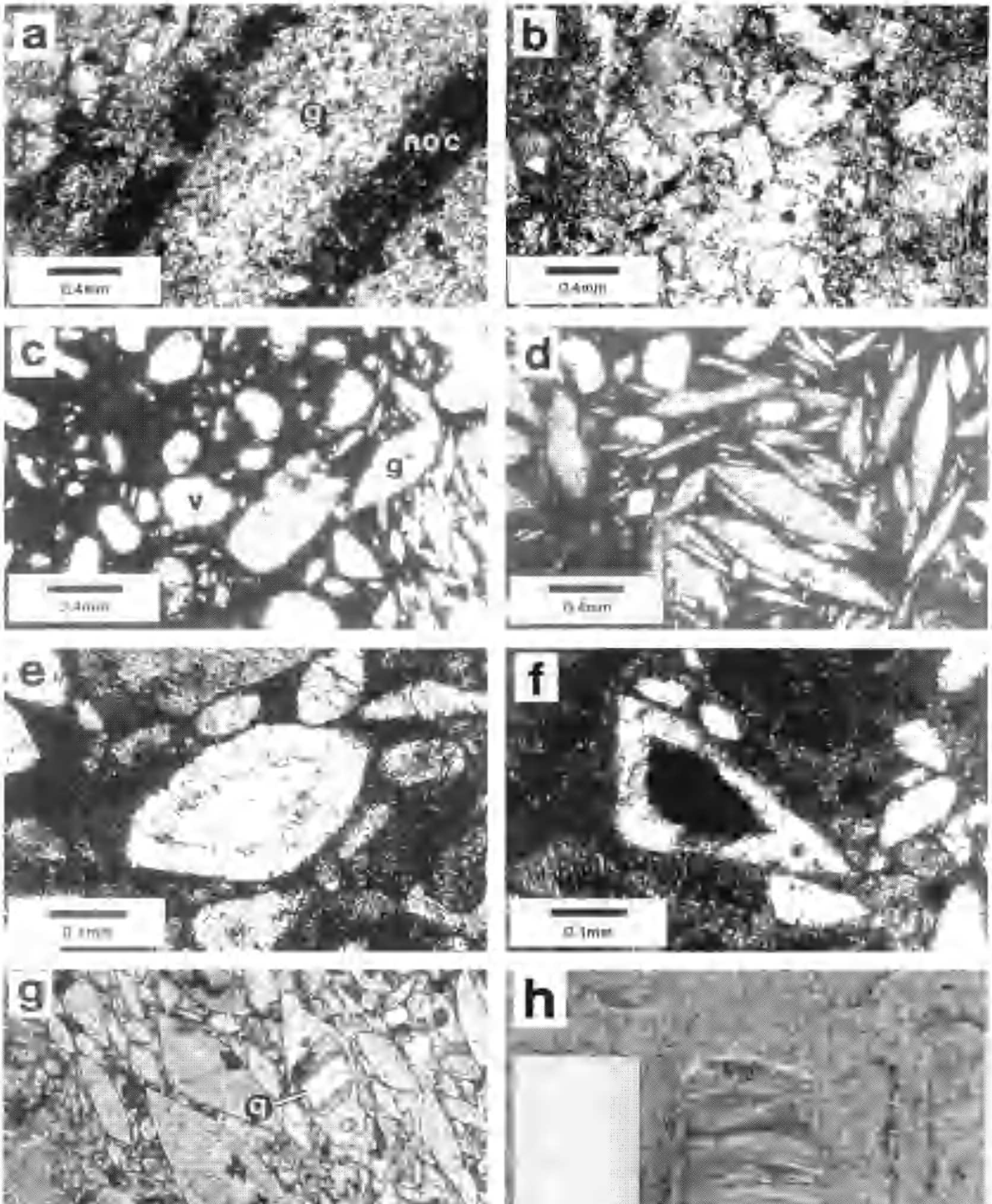
This unit consists of very light grey to light grey, heavy and very dense sericite clay containing randomly-oriented, displacive pyramidal gypsum. The gypsum is lenticular in thin section and displays a diversity of grain-size with crystals ranging from less than 1 mm up to 5 mm in length. The crystals are isolated and lack contact with each other. The poor sorting of the crystals reflects the variable porosity and permeability of the sericite matrix, which together determine the *in situ* growth of the pyramidal gypsum. The centres of the crystals frequently display polycrystalline overgrowths, seen as distinct crystal zoning under polarised light. Iron oxides are commonly incorporated along the cleavage planes of gypsum. The sericite matrix displays a high birefringence under crossed polars and is clearly the weathering product of the underlying unit. Unit 6 is approximately 70 cm in thickness in DH-5 and 3 m in thickness in DH-3, reflecting the irregularity in basement and variable depth of the weathering zone.

Unit 5: Laminated Gypsarenite

Unit 5 consists of finely laminated gypsarenite, which reaches approximately 1 m in thickness in DH-5 and disconformably overlies Unit 6 (Figs 2, 3a). The unit has not been recognised elsewhere in the basin and possibly represents local deposition within a deeper, central part of the basin. In fact, Unit 4 directly overlies Unit 6 in all cores with the exception of core DH-5. The gypsarenite comprises alternating wavy mm-thick laminae of very light grey fine to medium-grained, moderately to well-sorted sugary gypsum, coarser gypsum in a matrix of clay and dolomite, and medium light grey clay which drapes the underlying gypsum-rich laminae. Most of the gypsum crystals are prismatic and appear as equant polygons in thin section (Fig. 3a). The finer-grained gypsum is closely-packed, matrix-free, with only minor to trace amounts of fine-grained iron oxides. Prismatic gypsum comprising the coarser layers, on the other hand, occurs in a matrix of non-oriented clay and carbonate, predominantly kaolinite and saccharoidal dolomite, and displays concentrations of iron oxides along cleavage planes (Fig. 3b). Matrix-free, coarse-grained gypsum is also common but represents grading of the finer crystals rather than discrete laminae. Displacive, lenticular or pyramidal gypsum forms are rare but occasionally occur within the coarser gypsarenite layers, where they are oriented randomly or sub-vertically to bedding. Unlike the clay laminae comprising a more recent and better-preserved Unit 3, the clay in Unit 5 lacks optical orientation. A possible explanation for this is the relative abundance of coarse grains such as gypsum, quartz and iron oxides, which are incorporated in these laminae and prevent the clay particles from becoming aligned. Clay orientation may also be disrupted by post-depositional growth of gypsum within overlying and underlying layers.

Unit 4: Skeletal Peloidal Grainstone

Unit 4 consists of a strongly cemented skeletal peloidal grainstone, which disconformably overlies Unit 5 in DH-5 and Unit 6 in DH-1 to DH-4. The grainstone attains only 50 cm in thickness in DH-5 but reaches a maximum thickness of 3.5 m in the easternmost basin core DH-4, where it forms a unique and complex sequence of diagenetic carbonate-evaporite fabrics. These include moldic porosity filled by poikilotopic gypsum and dolomicrospar (Figs 4a, b), dolomicrospar and microspar cements containing displacive gypsum discoids (Fig. 4c) and dolomicrospar-coated allochems with a late pore-filling gyspsum cement (Fig. 4d). A possible explanation for the difference in unit thickness between DH-4 and DH-5 is that DH-4 is relatively proximal to the margin of the lake and is better suited for the deposition of sandy near-shore facies, in particular calcareous sands derived from surrounding sub-parabolic dunes. In DH-5, the grainstone is essentially a light olive grey, well-lithified gypsiferous wackestone with approximately 40-60% fabric-selective (moldic) porosity and displacive, poorly-sorted pyramidal gypsum within a micrite matrix (Figs 3c, d). The gypsum crystals occur as isolated laths, characterised by sharp crystal faces indicating minimal dissolution. Although the gypsum is generally randomly or sub-vertically oriented to bedding, individual crystals show a tendency for displacive


a
g
noc
0.4mm
b
0.4mm
c
v
g
d
e
0.1mm
f
0.1mm
g
g
0.4mm
h

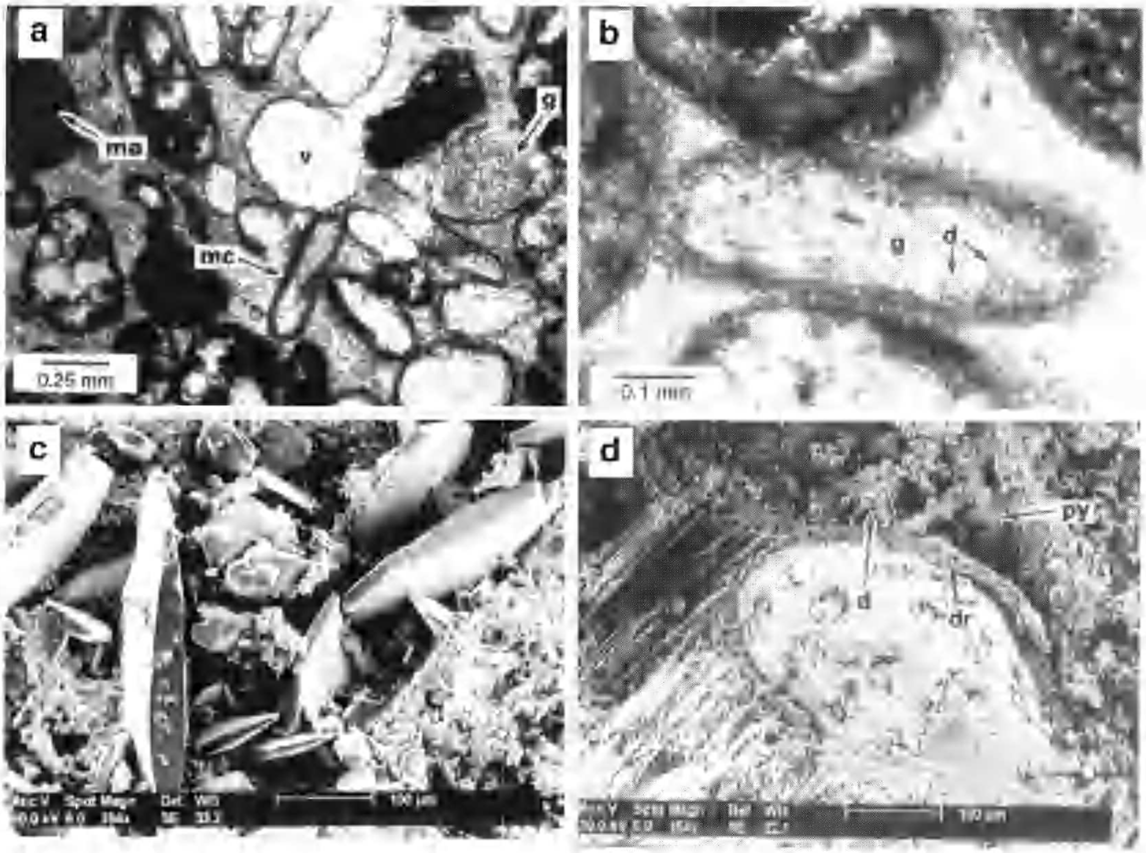


Fig. 4. Photomicrographs of the skeletal peloidal grainstone in Unit 5. Thin section images (a-b) taken under plain light. a) Moldic porosity partially filled by poikilotopic gypsum. Note micrite coatings (mc), micritised allochems (ma), empty allochemical voids (v) occasionally filled by gypsum (g). Intergranular cement consists almost entirely of poikilotopic gypsum (g). b) Allochemical void partially filled by anhedral dolomicrospar (d) and gypsum (g). Intergranular porosity is filled by poikilotopic gypsum and minor anhedral dolomicrospar. c) SEM image showing displacive gypsum discoids within a dolomicrospar/calcite microspar cement. d) SEM image showing a dolomicrospar rind (dr) around a micritised allochem. The rind forms contact sutures with neighbouring dolomicrospar rinds surrounding allochemical voids which are partially filled by dolomicrospar (d). Intergranular cement consists of poikilotopic gypsum and sparse dolomicrospar. Note the presence of intergranular pyrite (py).

Fig. 3. Photomicrographs of Units 3, 4 and 5 from the Lake Malata basin taken under plain light. (a) Gypsum-clay couplets in Unit 5. The thicker laminae consist of fine to coarse-grained equant (prismatic) gypsum (g) and the thinner laminae consists of non-oriented clay (noc) dominated by kaolinite. (b) Prismatic equant gypsum crystals in Unit 5. The matrix consists of kaolinite and dolomite. Iron oxides are commonly incorporated along the cleavage planes of gypsum. (c) Completely leached portion of the skeletal peloidal grainstone comprising Unit 4. Allochemical voids (v) are present within a dolomicrite matrix. Displacive discoidal (pyramidal) gypsum (g) is common and often forms clusters. (d) Abundant gypsum discoids in Unit 4. The discoids are randomly oriented to bedding and are rarely in contact with each other. (e) Pyramidal gypsum in Unit 3. Note zoning within the centre of the crystal caused by the inclusion of iron oxides around a pre-existing detrital core or gypsum nucleus. (f) Poorly-formed discoidal (pyramidal) gypsum crystal from the base of Unit 3. The centre of the crystal is occupied by a quartz core. (g) Gypsum discoids comprising the basal gypsarenite in Unit 3. The crystals are oriented sub-vertically to bedding and show zoning near the crystal edges related to dissolution and re-precipitation of the gypsum or variable growth rates of the single crystal. Quartz (?) (q) cores are occasionally present. (h) Core section showing regularly alternating laminae of gypsum (light) and clay (dark) comprising the gypsum-clay laminite in Unit 3 in DH-5.

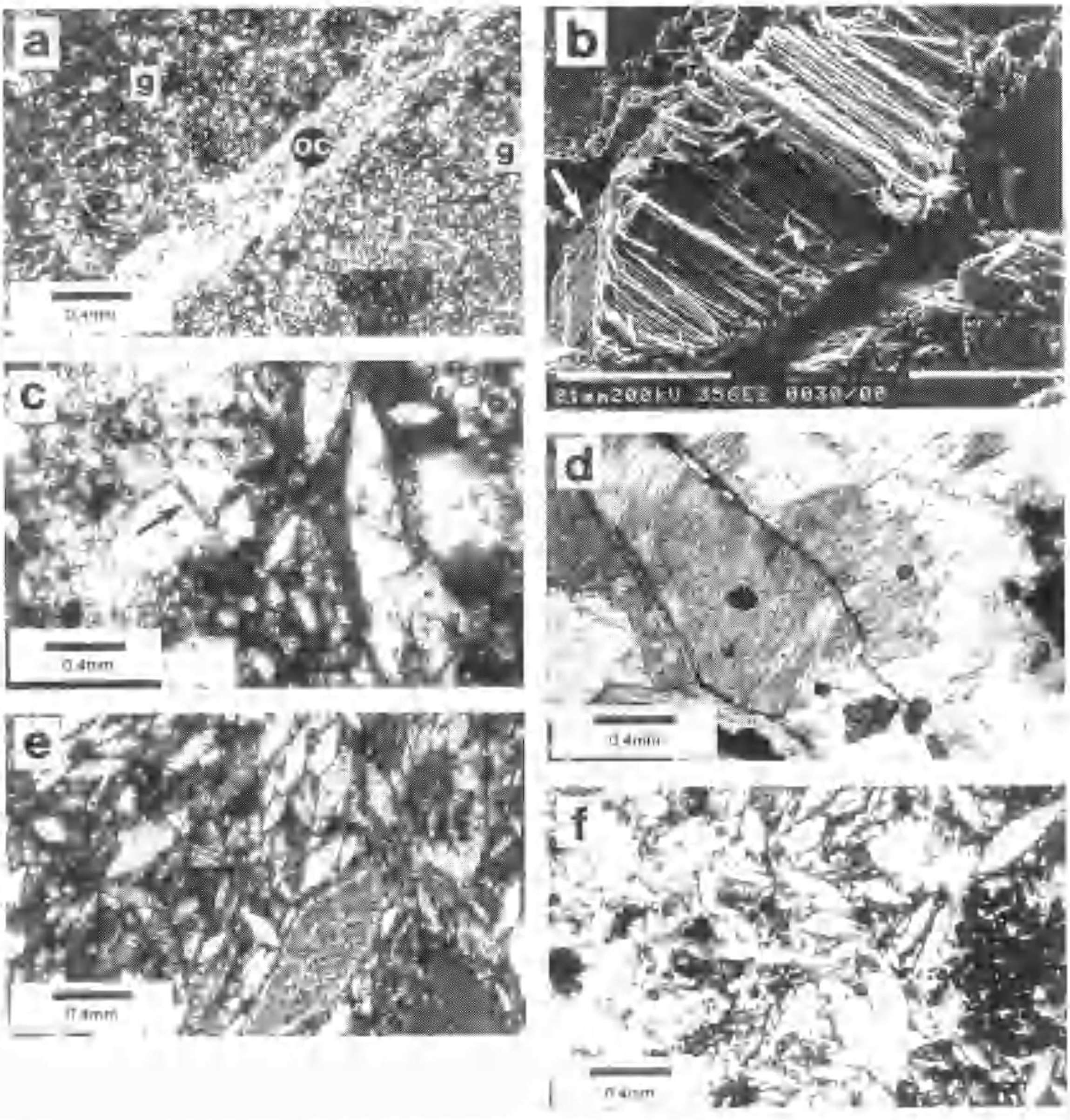


Fig. 5. Thin section (a, c–f) and SEM (b) photomicrographs showing the gypsum habits in Units 3 and 2. Polarised light (a), plain light (c–f). a) Gypsum-clay couplets comprising the gypsum-clay laminite in Unit 3. The laminae consist of highly oriented clay (oc) dominated by kaolinite, overlain and underlain by thicker layers of extremely fine-grained, equant, prismatic gypsum crystals (g). (b) Gypsum discoid (pyramidal gypsum) from the upper gypsarenite layer in Unit 3. The face of the crystal is the {011} cleavage plane which shows considerable recrystallisation. Note the presence of fine-grained sub-spherular dolomite (arrow). (c) Fracturing and minor reworking of a gypsum crystal (arrow) near the base of the upper gypsarenite horizon in Unit 3. Displacive (pyramidal) gypsum is the most common crystal morphology in this unit. The matrix consists of a mixture of kaolinite and dolomite. The gypsum is very poorly sorted. (d) Coarse, intergrown bladed (pyramidal) gypsum near the base of Unit 2 showing the presence of fibrous kaolinite (?) along the cleavage planes. Plain light. (e) Sub-vertically to randomly oriented discoidal (pyramidal) gypsum within a calcite-dolomite matrix comprising gypsarenite in Unit 2. Recrystallisation and zoning are particularly common in this zone. (f) Abundant iron oxides forming clusters within Unit 2.

sub-circular cluster arrangement (Fig. 3c) reminiscent of gypsite nodules. Preserved allochemical components in DH-4, as well as the general shape and size of the voids in DH-5, suggest that the porosity has resulted from a complete dissolution of skeletal and peloidal allochems sourced by the Bridgewater Formation. Detrital grains include fine-grained quartz, plagioclase and iron oxides, which have not been affected by dissolution. Grain counting and cluster analysis, although restricted to a small unleached portion of the unit in DH-4, show good correlation with the Bridgewater Formation and the 9 m beach ridge along the eastern margin of Lake Malata (Dutkiewicz *et al.* 2002). Although textures and fabrics described for DH-5 are consistent with pedogenesis, in DH-4 the skeletal peloidal grainstone has undergone extensive phreatic diagenesis which is reflected in fabric-selective moldic porosity, isopachous dolomicrospar rinds, intergranular and intragranular void-filling dolomicrospar, and poikilotopic and void-filling gypsum cement (Fig. 4).

Unit 3: Laminated Gypsarenite

Unit 3 disconformably overlies Unit 4 and attains a thickness of 6 m. It consists of a medium light grey to light grey gypsarenite containing variable amounts of interdispersed dolomite mud and kaolinite, fine-grained gypsarenite, and displacive gypsite nodules. The unit is interbedded with a finely laminated gypsarenite over the 9.5-10.5 m and 11.5-12 m depth intervals (Fig. 3b). The laminated sequences consist of alternating mm-thick wavy laminae of very light grey, sugary, fine to medium-grained, well-sorted gypsum, finer (~1 mm thick) laminae of medium dark grey, optically oriented kaolinite, and light grey mm-thick laminae of medium-grained gypsarenite in a matrix of clay and dolomite mud. Clay draping is common. A metre-thick layer of fine to medium-grained, moderately-sorted gypsarenite separates the laminated intervals.

The gypsum-clay laminae overlie a gypsarenite layer which consists of randomly and sub-vertically oriented pyramidal gypsum crystals within a matrix of saccharoidal dolomite (Fig. 3e). The gypsum crystals are relatively wide across the c-axis and show variable grain-size and degree of sorting. A cm-thick layer of pyramidal crystals oriented parallel to bedding, and showing little variability in grain-size, is also present. Zoning of crystals is common and may be attributed to: 1) the incorporation of iron oxides along cleavage planes and crystal boundaries during a change in the growth rate or during selective dissolution of the crystal (Fig. 3e); 2) crystal growth around a detrital core (Figs. 3f, g); 3) the development of gypsum overgrowths at the margins of gypsum crystals which lack optical continuity with the rest of the crystal. In this sense, the pre-existing gypsum crystals provide a nucleus for subsequent gypsum growth; and 4) selective dissolution followed by re-precipitation of central and marginal parts of crystals. All of these features have been observed in this part of the unit.

The repetitious nature of the clay and gypsum laminae bears a striking resemblance to similarly varved sequences from Lake Tyrrell (Bowler & Teller 1986), Prungle Lakes (Magee 1991) and Lake Eyre (Magee *et al.* 1995). In Lake Malata, the individual laminae consist of: 1) fine to coarse-grained, reversely graded, closely-packed, matrix-free, horizontally oriented prismatic gypsum; 2) relatively coarse-grained, frequently reversely graded, horizontally oriented, prismatic gypsum in a matrix of non-oriented clay (Fig. 3a). Here, the clay contains abundant iron oxides and minor fine-grained, displacive, vertically oriented pyramidal gypsum; and 3) optically oriented clay (kaolinite) with minor iron oxides and minor coarse-grained prismatic gypsum (Fig. 5a). The laminae are equally spaced and cyclic.

The gypsarenite overlying the gypsum-clay laminae consists of medium to coarse-grained, poorly-sorted, pyramidal gypsum in a matrix of non-oriented clay and saccharoidal dolomite with abundant gypsite nodules. The gypsum is randomly orientated to bedding and displays perfectly formed polycrystalline discoids under the SEM (Fig. 5b). A small number of the crystals, however, are prismatic and oriented parallel to bedding. The gypsite nodules are several mm in diameter, displacive and consist of silt-sized pyramidal gypsum forming matrix-free, cumulus-shaped clusters. Iron oxides are abundant and occur along cleavage planes of the pyramidal gypsum crystals. Fracturing and apparent reworking of a number of crystals are evident (Fig. 5c).

Unit 2: Gypsarenite

Unit 2 consists of yellowish grey to light olive grey, slightly muddy, medium to coarse-grained and poorly-sorted gypsarenite. The unit is approximately 5 m in thickness and sharply overlies Unit 3. The mud fraction consists of dolomite with minor amounts of detrital kaolinite, becoming increasingly calcite-rich (low-Mg calcite) towards the top of the unit where dolomite and kaolinite are present only in trace amounts. Kaolinite is occasionally incorporated within gypsum cleavage planes (Fig. 5d). Centimetre-thick laminations of relatively muddy gypsarenite alternating with less muddy gypsarenite are common between 4.5-5 m and 3.5-4 m. A decimetre-thick layer of greyish yellow green kaolinite is present between 5 and 5.4 m overlying a dm-thick layer of coarse-grained displacive discoids of pyramidal gypsum measuring about 1 cm in length. White, irregular and displacive gypsite nodules and gypsite layers are common between 5.5 and 6 m. In thin section, the gypsarenite consists of pyramidal crystals oriented randomly and sub-vertically to bedding dispersed within a carbonate (calcite and dolomite) matrix (Fig. 5e). Gypsum grain size is variable, with individual crystals ranging from less than 1 mm to 1 cm in length. Gypsite nodules also consist of randomly oriented pyramidal gypsum crystals. However, the crystals occur as poorly-developed discoids and form dense, displacive, matrix-free nodules within slightly muddy gypsarenite. Although detrital cores contribute to crystal zoning, the majority of the gypsum laths are zoned due to dissolution and rapid re-precipitation of gypsum (Fig. 5e). Large, bladed, occasionally fractured and intergrown, prismatic gypsum up to 1 cm in length is common near the base of the unit, where it shows replacement by low-Mg calcite (?) along the cleavage planes. Minor amounts of horizontally oriented prismatic crystals and clusters of iron oxide minerals (Fig. 5f) are also associated with this layer.

Unit 1: Gypsarenite

Unit 1 consists of olive grey, muddy, medium to coarse-grained, poorly-sorted gypsarenite interbedded with cm-thick layers of gypsite and a dm-thick layer of organic-rich, olive black low magnesian calcite mud near the base. The unit is approximately 70 cm thick and sharply overlies Unit 2. The gypsum is pyramidal, with individual long c-axes oriented randomly or sub-vertically to bedding. The crystals occasionally show inclusions of mud, indicative of fast growth rates within a mud matrix (Kastner 1970). Clusters of iron oxides are present locally. Only Unit 1 is represented within the piston core (C16; Fig. 1).

Interpretation of depositional environments

The stratigraphic sequence reflects largely groundwater-controlled oscillations in lake levels associated with humid and arid climatic episodes, which in a vertical sequence are marked by the presence of saline lacustrine facies (carbonates and evaporites), intermittent aeolian deposition of skeletal peloidal sand, lunette-building and pedogenesis of marginal regions.

Laminated clay-rich gypsarenite (Unit 5), which disconformably overlies weathered basement gneiss in the region, forms the base of the lacustrine sequence. The clay was most likely deposited in topographic lows as channel runoff during a relatively pluvial period, with flow and erosion initiated during and after heavy rains. Deposition may have occurred in the early Pleistocene prior to the initial emplacement of the sub-parabolic dunes ca. 700 ka (Wilson 1991)[1], which buried vast areas of the land surface and played a key role in the formation of the lake basins and the regional aquifer. This is supported by the absence of skeletal peloidal allochems within the clay which would otherwise be expected to be transported with the flow, with calcareous sand and grainstone occurring higher in the stratigraphic sequence. Lamination of clays in DH-5 in association with gypsarenite, suggests intermittent, possibly annual deposition controlled by the duration and frequency of the pluvial episodes. Regionally, the clay probably represents a relatively low flow regime, where only clay-sized particles with a very fine sand fraction are deposited in the centre of the basin.

Deposition of skeletal peloidal sands (Unit 4) is most likely related to Wilson's (1991)[1] phase I (ca. 400 ka) or early phase II (ca. 220 ka) emplacement of the Bridgewater Formation sub-parabolic dunes. The skeletal peloidal sand disconformably overlies basement clay and shows intense diagenesis and strong cementation in the centre of the Lake Malata basin. It is disconformably overlain by lacustrine gypsarenites in Lake Malata as indicated by sharp lithological discontinuities and the presence of indurated horizons above and below the unit, which are the result of subaerial exposure and pedogenesis. Deposition of Unit 4 is closely related to the Lake Malata foredune ridge, deposited during a prolonged pluvial phase ca. 319 ka (Dutkiewicz *et al.* 2002). The skeletal peloidal sand has undergone induration and cementation partly due to subaerial exposure and partly due to precipitation of phreatic intergranular cement, which reflects alternating groundwater fluctuations. The indurated (pedogenic) horizons indicate minor breaks in deposition of the sand, which is controlled largely by sediment supply and the intensity of the westerly winds. Relatively minor amounts of lacustrine carbonate have been deposited intermittently within the sand, forming discontinuous interbeds, as conditions became more pluvial for short-lived periods of time.

Vast amounts of the mobile skeletal peloidal sand would have been transported into the basin prior to dune stabilisation, during the landward migration of the dunefield and during subsequent episodes of dune re-activation. The sand was transported into the lake basin mostly by the strong prevailing westerlies

[1] Wilson, C.C. (1991) "Geology of the Quaternary Bridgewater Formation of the Southwest and Central South Australia" PhD thesis, The Flinders University of South Australia (Unpubl.).

and partly by local runoff which drained the sub-parabolic dunes. Emplacement of the first phase of skeletal peloidal sand initiated the formation of a major unconfined aquifer and the onset of lacustrine carbonate deposition. The lake at this time was relatively fresh, and the recharge rates high. The ca. 319 ka Lake Malata ridge and abundant dissolution features in the recharge aquifer and within the Lake Malata basin indicate evidence for high groundwater tables. Dissolution of allochems, particularly during the freshening recharge episodes, was essential in providing sufficient ions for the subsequent chemical precipitation of low-Mg calcite.

The skeletal peloidal sand experienced some reworking within the basin, as indicated by the presence of a relatively thin layer of the sand overlying laminated gypsarenite in DH-5. In this part of Lake Malata, the sand experienced induration and pedogenesis as reflected in the presence of a cryptocrystalline micrite cement and displacive pyramidal gypsum associated with a fluctuating water table. Pedogenesis appears to have been particularly effective in areas of lateral thinning of the sand/grainstone and may be related to the role of the grainstone as a recharge conduit and preferential drying of low recharge parts of the lake. Thick beds of skeletal peloidal grainstone, on the other hand, experienced intense diagenesis in the form of carbonate-evaporite fabrics related to oscillations in groundwater and the phreatic diagenetic environment (e.g., DH-4). In particular, carbonate cements formed during periods of increased pluviality, relatively low evaporation/inflow ratios associated with relatively high lake levels and low salinities. The dolomite represents a combination of replacive and void-filling cements linked with fabric-selective dissolution of allochems. Gypsum cements are void-filling and post-date carbonate cementation. They were formed during arid periods characterised by high evaporation/inflow ratios and low lake levels.

Following the first phase of dune migration (and formation of the calcareous recharge aquifer), the lakes were inundated with carbonate-enriched ground and surface water, with solutes derived largely through the dissolution of skeletal and peloidal allochems. This is evident in the first cycle of diagenesis in the skeletal peloidal grainstone within the basin, which is marked by the precipitation of carbonate cement, and in the considerable thickness of chemically-precipitated carbonate mud in regions of former lake extent overlying the first phase of skeletal peloidal sand deposition (Dutkiewicz 1996)'. The thickness and the relatively homogeneous nature of the carbonate units in marginal areas (Dutkiewicz 1996)' indicate that precipitation occurred under relatively long-lived hydrologically and climatically uniform conditions in a low energy, open-lake environment. The carbonate mud units correlate with laminated gypsarenite in Lake Malata (DH-5) from which several metres of carbonate have been removed by deflation during the construction of carbonate pellet lunettes over a period spanning ca. 96 to 15 ka (Dutkiewicz *et al.* 2002). It is possible that the indurated horizons separated by unlithified carbonate mud within these deposits are related to lunette pedogenesis associated with major falls in groundwater levels (Dutkiewicz *et al.* 2002). Possibly due to burial and moisture content, carbonate and clay pellets associated with lunette-building have not been detected at depth within the mud sequences.

Deposition of the skeletal peloidal grainstone in Lake Malata was followed by the onset of alternating shallow and relatively deep saline conditions associated with frequent groundwater fluctuations. This is illustrated by the presence of a distinct, finely laminated gypsarenite sequence (Unit 3) comprising alternating laminae of clay and prismatic gypsum, which overlies the skeletal peloidal grainstone towards the basin centre. In Lake Malata, carbonate sedimentation was restricted to marginal areas, proximal to the recharge aquifer, with gypsum deposition confined to central, deeper parts of the basin. The repetitive nature and constant thickness of the laminae in this unit suggest an alternating wet-dry, seasonal depositional cycle. Clays which comprise the thin ($<$ 1 mm) laminae and represent the fine-grained clastic component, were transported into the basin during the wet winter season as runoff which drained the eastern and western clay-rich slopes surrounding the lake. While the finer clastics were transported into the deeper, central parts of the basin, coarser clastics, including skeletal peloidal sand which is currently eroded from the sub-parabolic dunes bordering the southern lake margin, were deposited in the near-shore regions. Magee (1991) suggested that a density difference between the dilute inflow and concentrated lake brines would allow the fresh floodwater carrying a suspended clay to glide over the brine for considerable distances prior to the clay flocculating and settling to the lake bottom. Evaporation, combined with reduced inflow into the lake during the dry months, would subsequently concentrate the surface brine and allow prismatic gypsum to precipitate within the brine body or at the brine-air interface.

In Lake Malata, primary, subaqueous precipitation of gypsum is supported by: 1) the absence of reworking features such as fracturing and rounding, which are indicative of abrasion during transport, thus consistent with crystals growing at the sediment-water interface (Magee 1991); 2) the absence of variable grain size within a single gypsum laminae, which is indicative of diagenetic growth of crystals following deposition; and 3) the presence of wavy laminae, suggesting the presence shallow water. Therefore, gypsum comprising the laminae is of the "settled" variety of Magee (1991) having formed at the brine-air interface and then settled to the lake sediments as described by Schreiber *et al.* (1982). Coarsening-upwards of the gypsum crystals suggests that the surface brines became increasingly saline and supersaturated towards the end of the dry season, producing larger and fewer crystals (Schreiber 1978; Magee 1991). In order for subaqueous gypsum to precipitate and accumulate in significant amounts, the basin must be groundwater controlled and contain permanent saline water which is maintained only when the basin receives a constant supply of water and experiences high evaporation rates (Rosen 1994). The presence of clay within a number of the gypsum layers is related to brief flooding episodes during the dry phase, which apart from supplying fine-grained clastics to the lake, are insufficient to dilute the brine below the level of gypsum saturation. Iron oxides are supplied either during the flooding of the basin or are the product of sulphate-reducing bacteria oxidising iron sulphides. The cycle is repeated with the next wet episode, during which clay drapes the underlying gypsum. This provides an impervious layer which seals the gypsum and prevents it from undergoing dissolution, as the brine freshens by mixing with the dilute inflow.

Mechanisms involved in orientation of clay particles are not completely understood. A number of proposed mechanisms have been reviewed by Magee (1991), although to date very little work has been done on highly oriented clay particles. Most noteworthy contributions by Mead (1964) and Sonnenfeld (1984) suggested compaction, de-watering of clays and flocculation as possible controlling factors in particle alignment. Bowler and Teller (1986) suggested that formation and preservation of oriented clays in saline lacustrine environments is dependent on salinity and the activity of benthic micro-organisms. They proposed that deep water, aerated, low salinity environments would support scavenging organisms which are likely to disturb oriented clay particles. On the other hand, organisms cannot become established under conditions of extreme salinity and transported clays are able to flocculate and settle undisturbed. Since microfauna is relatively rare (or rarely preserved) in Lake Malata, the explanation of Bowler and Teller (1986) provides a likely mechanism for clay particle alignment in the laminae documented here.

Conditions following the seasonal deposition of the gypsum-clay laminite changed dramatically within the Lake Malata basin as lake levels dropped. This was due to an overall increase in the evaporation/inflow ratio caused by a decrease in precipitation, which is the main source of recharge into the lake, and/or a decrease in the fraction of groundwater lost due to leakage through an increasing impermeable skeletal peloidal grainstone (Dutkiewicz *et al.* 2000). Sediments directly overlying the laminated sequence are no longer varved and are dominated by pyramidal rather than prismatic gypsum (units 2 and 3). In fact, pyramidal gypsum is the most common form of gypsum within the evaporite beds and comprises thick units within Lake Malata and Lake Greenly. Pyramidal gypsum has been found in many coastal settings such as Hutt and Leeman Lagoons in Western Australia (Arakel 1980), Trucial Coast (Shearman 1966) and more recently in Lake Tyrrell (Bowler & Teller 1986) and Pringle Lakes (Magee 1991). Unlike prismatic gypsum, which forms within a standing brine body, pyramidal gypsum precipitates interstitially from saturated pore waters immediately below the sediment surface within the capillary zone under the influence of high evaporation rates (Bowler & Teller 1986). In Lake Malata, it is commonly found within a carbonate/clay matrix, where it either completely displaces the surrounding matrix forming mud-free gypsarenite, or undergoes diagenetic growth with gypsarenites becoming coarse-grained and poorly-sorted while isolated crystals become massive and reach several centimetres in length. Absence of solid inclusions within the massive gypsum indicates slow growth under uniform conditions (Kastner 1970). Pyramidal gypsum comprising gypsarenites, on the other hand, is generally cloudy due to the incorporation of impurities, suggesting fast growth under uniform conditions where the gypsarenites are moderately to well-sorted, and non-uniform conditions where the gypsarenite is poorly-sorted.

Bowler & Teller (1986) suggested that sediment layers containing abundant pyramidal gypsum crystals may be good indicators of past fluctuations in groundwater. The fact that pyramidal or discoidal gypsum comprises gypsum lunettes/foredunes along the eastern margin of Lake Malata in itself suggests seasonally oscillating hydrological conditions (Dutkiewicz *et al.* 2002). Since the gypsum lunettes/foredunes contain only traces of carbonate or clay pellets, it is the generally mud-free thick gypsarenite beds such as Units 3 and 2 which are the most likely source of the gypsum. In this scenario, gypsum is reworked by wave action during a relatively wet episode and deposited at the eastern lake margin, where it is subsequently deflated into a lunette or foredune during the next dry episode. The seasonal deposition of the gypsum foredune mimics the earlier deposition of the gypsum-clay laminae, which are no longer forming due to an overall drop in lake level and a shift from a throughflow to a relatively closed discharge basin. As advocated by Bowler (1983), near-surface precipitation of gypsum and other salts assists in pelletisation of lacustrine mud and clay. This process is required for deflation of mud and clay from the lake surface and is possible only under a groundwater discharge regime. The general absence of gypsum within carbonate pellet lunettes indicates that most of the gypsum precipitated as groundwaters rose slightly and the capillary fringe reached the lake surface, following a period of deflation and oscillating low water tables.

Units 1 and 2, which comprise the Lake Malata sequence, correlate well with the alternating carbonate-evaporite beds in Lake Greenly (Dutkiewicz & von der Borch 1995). However, correlation of individual beds is impossible, partly due to deflation of several metres of carbonate and its subsequent deposition along the north-eastern margin of Lake Malata (Dutkiewicz *et al.* 2002), and partly due to local hydrology, geomorphology and aquifer characteristics which control the deposition of carbonates in one basin and evaporites within the other basin. However, within a single vertical sequence, the carbonate beds are associated with humid conditions and relatively low evaporation/inflow ratios, whereas the gypsum is associated with arid conditions and relatively high evaporation/inflow ratios. Thermoluminescence dating of carbonate-pellet lunettes suggest that these humid-arid oscillations may have been operating since ca. 16 ka, which post-dates the majority of carbonate pellet lunette deposition and overlaps with formation of the gypsum lunette/foredune ca. 5.6 ka cal BP (Dutkiewicz *et al.* 2002).

Acknowledgments

A. Dutkiewicz gratefully acknowledges the financial support of Flinders University. We thank Joe Lorenzin for the preparation of thin sections and staff at the DME core library and the CEMMSA at Adelaide University for their help with accessing and analysing the Lake Malata sediments. Core C16 was sampled with the help of fellow Flinders University post-graduate and honours students. We are indebted to the Modra Family for their hospitality and help during our prolonged stays in the field. Chris von der Borch acknowledges the continuing support of the School of Physics, Chemistry and Earth Sciences at Flinders University. We thank Martin Williams for a thorough review of the manuscript.

References

Arakel, A. V. (1980) Genesis and diagenesis of Holocene evaporitic sediments in Hutt and Leeman lagoons, Western Australia. *J. Sed. Pet.* **50**, 1305-1326.

Bowler, J. M. (1983) Lunettes as indices of hydrologic change: a review of Australian evidence. *Proc. Royal Soc. Vic.* **95**, 147-168.

_______ & Teller, J. T. (1986) Quaternary evaporites and hydrologic changes, Lake Tyrrell, north-west Victoria. *Aust. J. Earth Sci.* **33**, 43-63.

Dutkiewicz, A., Herczeg, A. L. & Dighton, J. C. (2000) Past changes to isotopic and solute balances in a continetal playa: clues from stable isotopes of lacustrine carbonates. *Chem. Geol.* **165**, 309-329.

_______ & von der Borch, C. C. (1995) Lake Greenly, Eyre Peninsula, South Australia: sedimentology, palaeoclimatic and palaeohydrologic cycles. *Palaeogeog., Palaeoclim., Palaeoecol.* **113**, 43-56.

_______, _______ & Prescott, J. R. (2002) Geomorphology of the Lake Malata-Lake Greenly Complex, South Australia, and its implications for Late Quaternary Palaeoclimate. *Trans. R. Soc. S. Aust.* **126**, 103-115.

Kastner, M. (1970) An inclusion hourglass pattern in synthetic gypsum. *Am. Mineral.* **55**, 2128-2130.

Magee, J. W. (1991) Late Quaternary lacustrine, groundwater, aeolian and pedogenic gypsum in the Prungle Lakes, southeastern Australia. *Palaeogeog., Palaeoclim., Palaeoecol.* **84**, 3-42.

_______, Bowler, J. M., Miller, G. H., & Williams, D. L. G. (1995) Stratigraphy, sedimentology, chronology and palaeohydrology of Quaternary lacustrine deposits at Madigan Gulf, Lake Eyre, South Australia. *Palaeogeog., Palaeoclim., Palaeoecol.* **113**, 3-42.

Meade, R. H. (1964) Removal of water and rearrangement of particles during the compaction of clayey sediments - review. *U.S. Geological Survey Professional Paper*, No. 497-B, 23 pp.

Rosen, M. R. (1994). The importance of groundwaters in playas: A review of playa classifications and the sedimentology and hydrology of playas. *In* Rosen, M.R. (Ed.) "Paleoclimate and Basin Evolution of Playa Systems" Geol. Soc. Am. Special Paper No. 289.

SCHREIBER, B. C. (1978) Environments of subaqueous gypsum deposition. pp. 43-73 *In* Dean, W. E. & Schreiber, B. C. (Eds) "Marine Evaporites" SEMP Short Course No. 4. Soc. Econ. Min. Palaeont., Tulsa, U.S.A.

__________, ROTH, M. S. & HELMAN, M. L. (1982) Recognition of primary facies characteristics of evaporites and the differentiation of those forms from diagenetic overprints pp. 1-32 *In* Hanaford, C. R., Loucks, R. G. & Davies, G. R. (Eds) "Depositional and Diagenetic Spectra of Evaporites - A Core Workshop" SEMP Core Workshop 3, Calgary.

SHEARMAN, D. J. (1966). Origin of marine evaporites by diagenesis. *Inst. Min. Met. Trans.* **75**, 208-215.

SONNENFELD, P. (1984). Brines and Evaporites. (Academic Press, New York, U.S.A.).

WARREN, J. K. (1982) The hydrological setting, occurrence and significance of gypsum in late Quaternary salt lakes in Australia. *Sedimentology*, **29**, 609-637.